Earthquake Monitoring and Response from Space: The TREMOR Concept

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Abstract

Earthquakes and their after-effects claim thousands of lives and cause enormous property damage each year. Early warning of impending seismological events has the potential to reduce human suffering and physical damage resulting from these natural disasters. Reliable earthquake precursors have yet to be identified, but some research is currently being performed into phenomena that could be observable from space. Satellites have been unquestionably beneficial in the response to earthquakes, providing essential communication and remote sensing support. The Technological Resources for Earthquake MOnitoring and Response (TREMOR) concept was initially developed as a team project at the 2007 International Space University Summer Session Program. It recommends the establishment of an international non-governmental organization that can more efficiently co-ordinate space-based and ground-based resources for the protection of human lives and property. The TREMOR concept is explored further here, concentrating on its use of space technology to minimize the economic and human impact of earthquakes. Updated cost estimates for TREMOR satellite mission concepts are also presented.

Introduction

Earthquakes are among the costliest and deadliest of natural disasters. Figure 1 shows the number of deaths and cost of damage resulting directly from earthquakes for the years between 1990 and 2006 inclusive, based on data obtained from the National Geophysical Data Center.

Behind these numbers lies a grim dichotomy. The earthquakes with the highest economic cost occurred in developed nations, such as the United States (Northridge, California, 1994) and Japan (Kobe, 1995). The human loss was greatest, however, in developing nations such as Turkey (Izmit, 1999), India (Gujarat, 2001), Iran (Bam, 2003), and Pakistan (Kashmir, 2005). This all-too-familiar pattern stems from the disparity in available resources between the populations of the different countries, whether it applies to the degree of economic wealth exposed, to the prevalence of seismically-resistant construction practices, or to the infrastructure required to prepare for and respond to such disasters. Rapid population growth and urbanization in many developing nations has also increased human risk, particularly when migrant populations concentrate in areas susceptible to earthquakes, in housing that is typically of poor construction.

Space already plays a prominent role in the global effort to minimize the economic and human impact of earthquakes, as it does for all natural disasters. Remote sensing satellites provide crucial data on land use and on damage resulting from earthquakes, while telecommunications satellites provide essential support for response crews when local communication lines are overloaded or unavailable. A factor that distinguishes earthquakes from most other natural disasters, however, is the lack of a reliable early warning system. Weather patterns can be tracked by meteorological satellites, but present systems cannot detect an earthquake until minutes or seconds before it occurs. Interferometric synthetic aperture radar (InSAR) has been successfully used to monitor minute ground displacements, and shows considerable promise as a means for monitoring tectonic deformation on a global scale. Within the last decade, attempts have also been made to observe electro-magnetic phenomena from space that could be connected with seismic activity. Results of these studies have to date been of mixed success, and the study of electro-magnetic earthquake precursors is regarded in many in the field as controversial. Nevertheless, a number of satellite missions are being proposed to carry this research further.

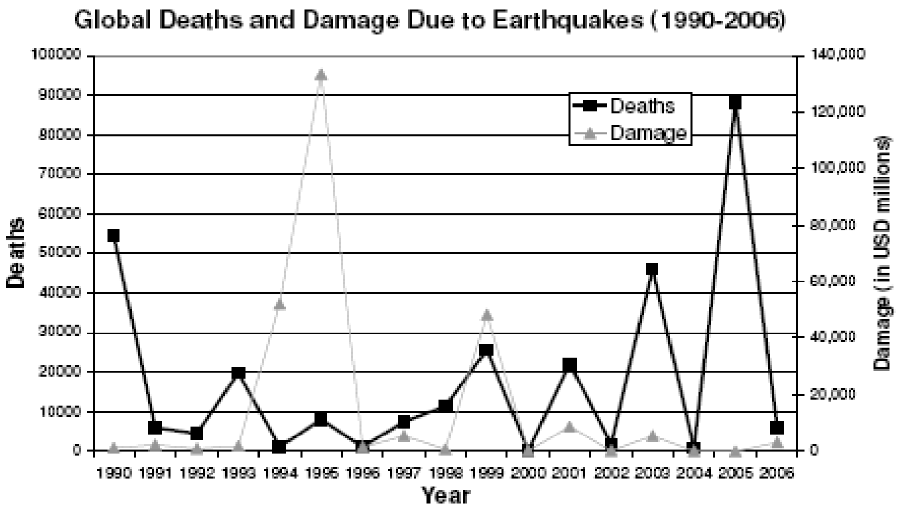

Figure 1: Global Deaths and Damage due to Earthquakes (1990-2006) [1][2]

In August 2007, a report addressing the role of space in earthquake monitoring and response was issued by a team of 36 students attending the Summer Session Program (SSP) of the International Space University (ISU), hosted by Beihang University in Beijing, China. The authors of this paper were all members of this team. The report recommended the introduction of a new non-governmental organization (NGO) responsible for coordinating space-based and ground-based resources in responding to earthquakes, and for supporting research into potential space- and ground-based methods for providing earthquake early warning. Referred to as the TREMOR Foundation (Technological Resources for Earthquake MOnitoring and Response), the NGO would implement two parallel prototype systems for response and early warning in three focus countries – China, Japan, and Peru – that are susceptible to earthquakes. If demonstrated successfully in the focus countries, these systems would be expanded to other countries as well.

This paper briefly summarizes the findings of the TREMOR report and presents original and updated research on the early warning prototype, highlighting results from recent studies on earthquake precursors. It then takes a more in-depth look at the satellite constellations that were proposed for this purpose, updates the cost estimates for these constellation options, and examines where NGO funding can be most effectively applied to advance the science.

Earthquakes and Earthquake Precursors

Earthquakes occur as a result of the release of stresses in the Earth's crust. Principal causes of earthquakes include slippage of two plates along a fault line, subduction of one plate under another, excessive subterranean heat flow, and volcanism. [1] The vast majority of earthquakes occur along tectonic plate boundaries, as seen in Figure 2, although intra-plate earthquakes can also occur. Earthquakes occurring beneath the ocean can wreak additional havoc by generating powerful tsunami waves, such as those that devastated regions in the eastern Indian Ocean on December 26, 2004, killing upwards of 150,000 people. [5]

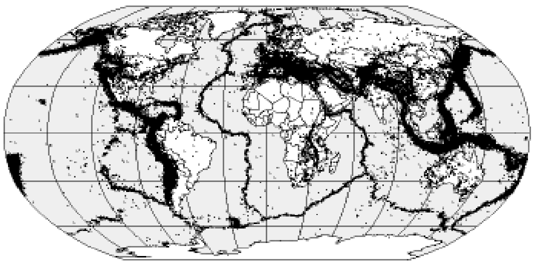

Figure 2: Global Earthquake Distribution [18]

The sites of greatest earthquake activity in Canada occur in the Pacific Ocean to the west of British Columbia, where the Juan de Fuca oceanic plate is subducting under the North American continent, and in the St Elias mountain range along the Alaska/Yukon border. The most powerful Canadian earthquake in the last century occurred on August 22, 1949 in the Queen Charlotte Islands (Haida Gwaii) and had a Richter scale magnitude of 8.1.[1] [6]

Earthquakes are typically detected by seismometers up to several minutes before the point of maximum release, when the first seismic waves propagate through the crust. If an impending earthquake could be detected much earlier– days or even hours in advance – such that a watch or warning could be issued to the affected area, the human and economic devastation could be substantially reduced. Unfortunately, a reliable ability to forecast earthquakes this far in advance does not yet exist. Research is presently being conducted into possible earthquake precursors that – if proven reliable – might in the future allow such a capability. Two of these possible precursors are discussed here, both of which feature a space component.

Tectonic Stress Precursors

Seismologists presently detect earthquakes based on the pressure waves generated by the event itself. The first established signals therefore occur at the time the energy is being released. Prior to this release, however, stress has been gradually accumulating in the crust as a result of friction or excessive heat flow. If this stress can be monitored directly, it could give some warning that a release is pending.

Stress is directly related to strain – the deformation of the material under stress – and the strain is typically what can be most easily measured directly. Ground-based studies of crustal movements and deformation involve equipment such as tilt sensors and strain gauges. An example is the network of tilt sensors located in the Apennine Mountains of Italy operated by a team from the University of Rome Tre. [10] Tectonic motion (or lack thereof) can also be observed from orbit, over a wider area, using either GPS or InSAR. These technologies are addressed in more detail in the section entitled “The Role of Space”. Another technology being employed frequently in seismic mapping is laser-imaging radar (LIDAR). Airborne LIDAR surveys have been conducted over major fault regions, and could conceivably be done from orbit as well. Unlike GPS and SAR, however, LIDAR cannot penetrate cloud cover, which would limit its use for continuous ground motion monitoring.

EM and Ionospheric Precursors

On October 17, 1989, a 7.1-magnitude earthquake struck the San Francisco Bay area, centred near Loma Prieta in the Santa Cruz Mountains. Anthony Fraser-Smith, a researcher in geophysics and electrical engineering at Stanford University, detected a 20-fold increase in the

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[1] An earthquake occurred on January 26, 1700 in the Cascadia subduction zone, which stretches between Vancouver Island and Northern California, and is estimated to have had a magnitude of 9.0. The resulting tsunami waves reached across the Pacific Ocean, and were noted by contemporary Japanese chroniclers.

extra-low-frequency (ELF) magnetic field intensity for 12 days immediately preceding the earthquake at a geomagnetic monitoring station less than 8 km from the epicentre. The elevated signal (in the range of 0.01-0.02 Hz) peaked at the time of the earthquake and persisted for several months afterward. [3][4] This represents one of the best known observations of low-frequency electromagnetic (EM) activity in conjunction with earthquakes.

Claims of seismogenic EM phenomena observed from space have also been made, including anomalous magnetic field measurements made by the Soviet Cosmos 1809 and French Aureol-3 missions shortly after the 1988 Spitak earthquake in Armenia. [3][7][8] These observations have led to interest in some quarters in so-called "seismological electromagnetic emissions" (SEME), and various research groups have since been attempting to confirm the phenomenon.

What could cause EM emissions prior to, during, or after an earthquake? And why would some or any of these emissions be observable from space? It must be stated that there is no generally accepted theory, and in fact many researchers in the seismological community cast doubts on the usefulness of this phenomenon for earthquake forecasting, or even on its very connection to seismic activity. Many hypotheses, however, point to piezo-electric and/or piezo-magnetic effects as a result of the immense stresses that build up in the crust. [22] Friedemann Freund of NASA Ames Research Center, for example, observed two opposing currents – an electron current and an electron hole (or "p-hole") current – when stress was applied to a rock sample in a laboratory. [9] Other hypotheses for SEME involve the transport of charged particles in sub-surface fluid flow resulting from the seismic stress. [20] [21]

Vittorio Sgrigna of the University of Rome Tre posits that most high-frequency SEME are attenuated by the intervening rock, leaving only low-frequency (ULF/ELF) waves to reach the surface, and that only in the case of strong and/or moderate-depth earthquakes do higher-frequency SEME make it to the surface and enter the near-Earth space. Energetic particle bursts in the South Atlantic Anomaly (SAA) region in connection with seismic events have also been reported, possibly resulting from interactions of SEME with trapped particles in the Van Allen belts, which then cause some of these particles to precipitate back to lower altitudes. [10]

Despite the reported observations on missions such as Cosmos-1809 and Aureol-3, only three satellites specifically dedicated to the study of SEME have been launched to date, and only within the past few years: QuakeSat (2003), DEMETER (2004), and Compass-2 (2006). These missions are described in more detail in the following section of this paper.

Possibly connected to the SEME phenomena are observations of ground heating at least several hours prior to an earthquake, such as that observed by the Landsat thermal infra-red imager prior to the Hector Mine, California earthquake in October 1999, and by the Terra imager prior to the Gujarat, India earthquake in January 2001. [23][24] Pressure-driven fluid flow has been put forward as an explanation for this as well, but some advocates of the piezomagnetic hypothesis suggest that the IR emissions are generated instead by electron-hole recombination rather than by actual surface heating. [20][24]

Although genuine science is being conducted in the area, it must be emphasized that ionospheric precursor research is still very much in its infancy, and the hypothesized coupling between the lithosphere and the ionosphere remains unproven.

The Role of Space

The value of satellite technology in disaster management cannot be overestimated, and the specific case of earthquakes is no exception. What follows is a discussion of the major roles of satellites in earthquake planning, mitigation, response, and recovery. A detailed synopsis of the satellite missions and technologies involved is beyond the scope of this paper. Instead, the reader is directed to the TREMOR report for further background. [1]

Remote sensing – primarily electro-optical and radar – is employed to assemble databases on building stock and land usage in seismically active regions, which is in turn used for risk assessment and for disaster preparation. In the aftermath of an earthquake, remote sensing provides images of the disaster region that help identify the areas most impacted and in need of assistance. Synthetic aperture radar (SAR) technology is of particular value in these situations, as SAR imaging is not restricted by lighting conditions or cloud cover. Image processing techniques exist to subtract post-disaster images from stock images of the same region prior to the disaster, enabling identification of the areas most heavily afflicted.

Telecommunications satellites provide many crucial services in disaster situations, including telephone coverage for relief crews when local landlines and cellular networks are inoperative or overwhelmed. Live visual feeds from the disaster zones are also used for damage assessment and for delivering telemedicine.

The Global Positioning System (GPS) is used for navigation and tracking of relief crews and emergency vehicles inside the disaster region. GPS is also used in seismic research, as minute movements in the Earth's crust (on the order of centimeters or less) can be deduced using large numbers of receiver stations mounted close to known fault lines.

As indicated previously, no system currently exists (space-based or otherwise) that can provide early warning of an impending earthquake. QuakeSat and DEMETER are two recent satellite missions that have investigated the link between ionospheric activity and seismic events. There are also a number of mission concepts on the drawing board for further study of both stress-based and ionospheric precursors. These missions are described in the following subsections.

Tectonic Stress Precursor Missions

Monitoring crustal movement requires sub-centimetre precision. GPS signals received at multiple ground stations can be averaged to achieve these levels. This can be an effective method for monitoring specific regions known to be at seismic risk, but installing permanent receiver stations on a global scale is far less practical.

InSAR is a remote sensing technique employed since the 1990s to measure small surface deformations. Phase shifts in the reflected radar pulses between multiple passes over the same region can measure line-of-sight displacements to less than 1 cm in many cases, although surface vegetation and atmospheric refraction can limit this capability. Measurements taken from different vantage points are required to construct a multi-dimensional picture of ground movement. Operating satellites with InSAR capability include Radarsat 1 and 2 (Canada), Envisat (Europe), TerraSAR-X (Germany), COSMO-SkyMed (Italy), and ALOS (Japan). ERS 1/2 (Europe), and JERS (Japan) provided InSAR data in the past, but are no longer operational. [1]

In 2003, the NASA Solid Earth Science Working Group (SESWG) released a study evaluating future options for InSAR-based seismic monitoring. It proposed, at minimum, a high-LEO orbiting SAR satellite operating in the L-band (23.5 cm), which is less sensitive to ground motion due to the longer wavelength, but is also much less affected by ground vegetation than the more traditional C-band SAR. The proposed altitude of 1325 km, higher than any previous SAR mission, would require a larger antenna to compensate for the increased range and would reduce spatial surface resolution, although interferometric resolution of the ground displacements would not be affected. The higher altitude would allow a larger swath width, reducing revisit time to less than 64 hours for any point on the Earth, and thus make it a better system for global tectonic monitoring. In the GESS roadmap, this pilot mission would later be complemented by up to three other high-LEO satellites offering even better repeat times, with 90% of the surface being revisited within 6 hours.

Towards the end of its 20-year plan, the GESS report envisions a far more ambitious program, with a SAR constellation of up to ten satellites in inclined geosynchronous orbits to improve the repeat time even further, with 90% of the surface revisited within 2 hours, and to achieve interferometric resolutions on the order of millimetres through averaging. Such a constellation would require antennas with a minimum 30-m diameter, requiring antenna deployment technologies not yet fully developed. The SESWG estimates the per-satellite price tag for the high LEO concept at USD 400-500 million, and for the geosynchronous concept at USD 1-2 billion. [19]

EM and Ionospheric Precursor Missions

QuakeSat is a 4.5-kg nanosatellite built by a student team at Stanford University and funded by QuakeFinder, a private corporation based in Palo Alto, California. Quake-Sat-I was launched on June 30, 2003 on a Eurockot launch vehicle[2]. Its payload consists of a search-coil magnetometer with a scanning frequency range of 0.5 to 1000 Hz and a secondary electric field sensor. The intent was to search for and characterize field intensity fluctuations similar to that observed by Cosmos-1809 following the Spitak earthquake.

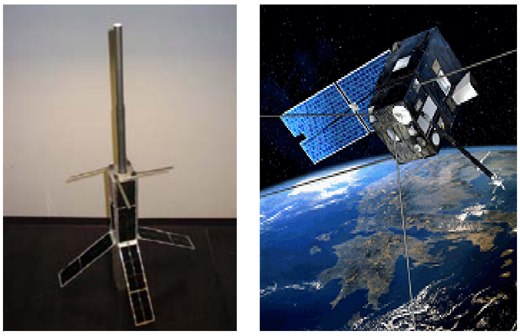

Figure 2: QuakeSat (left) and DEMETER

The magnetometer on QuakeSat experienced higher-than-expected noise levels on orbit due to its short boom, which limited its capabilities, but did detect a number of field intensity bursts in the 10-100 Hz range between a few days and 8 weeks prior to three earthquakes in late 2003 – Japan (October 31), San Simeon, California (December 22), and Iran (December 26). The number of samples obtained of these bursts was small, due to the short flight duration over each region. The observed bursts were also very short in duration, lasting a few seconds at most, which indicates a potential difficulty in monitoring for them in orbit. [32] QuakeSat suffered a failure of both batteries in January 2004, and since then has not been able to power the science instruments, although it received sufficient power to remain alive, due to its dawn-dusk sun-synchronous orbit, delivering data and responding to ground commands. The mission was active for a total of 18 months, delivering 2 GB of data. In January 2005, it was placed into a dormant mode. A microsatellite-class mission called QuakeSat-II was proposed by QuakeFinder, but has not yet been funded. QuakeFinder also manages the California Magnetic Network (CalMagNet), a ground-based network of ULF magnetometers near the San Andreas Fault that scan for SEME closer to the earthquake origin. [3]

In July 2004, the French microsatellite DEMETER (Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions) satellite was launched into a 715-km sun-synchronous orbit. The primary science payload of DEMETER consists of a search-coil magnetometer, electric field sensors, plasma analyzers, and a particle detector. A neural network tool is used to sift through the science data stream for seismic correlations. The satellite is operated by Laboratoire de Physique et Chimie de l'Environnement (LPCE). [11]

[2] This launch was shared with two Canadian satellites – the MOST space telescope and the CANX-1 student nanosatellite.

Aurora Buzzi, a doctoral student working under Sgrigna at the University of Rome Tre, analyzed telemetry from DEMETER and found a positive temporal correlation between the occurrence of seismic events and “whistlers” – transient low-frequency EM waves similar to those generated by lightning. Buzzi did not find a distinction between whistlers occurring before, during, or after earthquakes, however, and results from the particle detector did not show a correlation between particle bursts and earthquakes. [12] Such a correlation had been previously reported based on data from the NASA SAMPEX mission. [13]

In May 2006, a Russian microsatellite called COMPASS-2 (Complex Orbital Magneto-Plasma Autonomous Small Satellite) was launched into a 401 x 488-km, 80°-inclination, drifting orbit, carrying an international payload that included a low-frequency wave detector and a GPS-based total-electron-content (TEC) analyzer. Technical problems prevented science operations from beginning until Nov 2006, and the satellite was decommissioned in July 2007. Literature describing results from the mission could not be located at the time of writing. [14] [15]

In the wake of these first ionospheric precursor missions, some other concepts are being put forward. ESPERIA is an Italian microsatellite concept proposed as a follow-on mission to DEMETER. Three of the ESPERIA payloads have already been demonstrated in space – a search-coil magnetometer and particle detector (carried on board the International Space Station) and an additional particle detector (carried on board the Russian Resurk-DK1 satellite). The satellite is proposed to have a near-equatorial orbit at 800 km altitude, with a tightly repeating ground track. Ground-based tilt and EM sensors would provide corroborating data. [10]

A Japanese concept for an Electric and Magnetic field Observation Satellite (ELMOS) to conduct earthquake precursor research has been proposed since at least 1998, but does not yet appear to have secured funding. [16] A Chinese concept called the Chinese Seismo-Electro-mechanical Satellite (CSES) has also been put forward. [17]

Due to the infancy of this field of research, and due to the mixed results from the first few missions, ionospheric precursor research from space is likely to be restricted for the near future to microsatellite and nanosatellite class missions, which require a comparatively small financial investment. Fortunately for SEME advocates, EM payloads tend to be less expensive than alternatives (e.g. SAR), and can be used to perform complementary science in the field of space weather. Should future results from space prove more conclusive, government agencies and other space players may be willing to make more substantial investments. For the time being, however, overall space activity in this area remains limited.

Disaster Management and the TREMOR Concept

Disaster management occurs in a cycle of four phases: planning, mitigation, response, and recovery [29], as shown in Figure 3. Planning consists of activities to analyze and document the likelihood of a disaster and the potential consequences on life, property, and environment. [28] The mitigation phase can be defined as the “measures taken in advance of a disaster aimed at decreasing or eliminating its impact on society and environment”. [30] Early warning of impending events such as earthquakes is therefore considered part of this phase. The response phase includes the set of “decisions and actions taken during and after disaster, including immediate relief,

Figure 3: Disaster Management Cycle

rehabilitation, and reconstruction”. [30] The recovery phase encompasses the activities, both short- and long-term, necessary for returning society to normality after a disaster. Recovery activities may continue for years after the occurrence of a disaster. [28]

An additional term often used is disaster reduction. Disaster reduction can be defined as “the conceptual framework of elements considered with the possibilities to minimize vulnerabilities and disaster risks throughout a society, to avoid (prevention) or to limit (mitigation and preparedness) the adverse impacts of hazards, within the broad context of sustainable development”. [31] Disaster reduction can be thought of as an overall strategy or goal that encompasses all of the phases of the disaster management cycle.

The disaster management cycle is a continuous process, and the four phases tend to blend together in many circumstances. Activities within the four phases are implemented by a wide range of actors, including local, national and supranational governments, individual citizens, non-governmental organizations (NGOs), and private companies. As a result, the disaster management process often in practice lacks coordination. The TREMOR proposals are in part motivated by a desire to reduce this lack of coordination.

During the course of its work, the TREMOR Team researched NGOs operating in disaster management arenas and identified a large number focused on activities in the response and recovery phases, but very few involved in the mitigation phase.

TREMOR Foundation

Recognizing the existence of these gaps in the disaster management process, the TREMOR report recommended the establishment of a new non-governmental organization (NGO), provisionally referred to as the TREMOR Foundation, that would implement systems to coordinate disaster management efforts in the area of earthquakes and to advance the science behind earthquakes with the hope of one day establishing an operational early warning system, if feasible.

Operating as an NGO offers numerous advantages over other organizational structures. A non-profit NGO has significantly more flexibility in funding options than either a for-profit entity or an intergovernmental agency. As an NGO, the TREMOR Foundation would not be dependent on a single funding source, but would instead be able to select from a range of options. Depending upon the jurisdiction in which the Foundation is headquartered, additional tax benefits and savings may be obtained that might not be available to a for-profit institution. An NGO can be established without the lengthy treaty-based process required for an intergovernmental organization and it can more easily obtain commercial licenses for satellite data. Finally, as an NGO, the Foundation would have the legal standing to conduct its own international arrangements. For example, the Foundation could seek to have observer status at the COPUOS, consultative status at ITU and WMO, and participation in the Committee on Earth Observing Satellites (CEOS) and the Group on Earth Observations (GEO). [29]

Government support for the NGO will be essential in early phases of implementation, as the technology is being evaluated. While a successful earthquake early warning system could be made financially self-supporting as a result of its potential to save costs each year through damage reduction, during the pilot period the performances of these systems would not be sufficiently demonstrated and would be less likely to attract private investment. It is proposed, however, that even in the early stages the Foundation develop commercial spin-off opportunities via a for-profit subsidiary, which could provide additional funding to the Foundation through dividends. The subsidiary could earn income by selling data products to earthquake insurance markets and to geographic information system (GIS) providers, and by developing disaster recovery plans for industry and government organizations.

Prototype Systems

The TREMOR report envisioned a 10-year pilot period, during which prototype systems to address early warning and disaster response issues would be implemented. These prototype systems would be established during the pilot period in three focus countries. For the TREMOR report the focus countries were selected to be China, Japan, and Peru, to obtain a suitable cross-section of developed and developing countries that have a high incidence of earthquakes.[3]

The early warning prototype would attempt to advance the science and technology behind earthquake precursors and precursor monitoring, while in parallel establishing policy and procedures on earthquake early warnings so that if reliable precursors can one day be demonstrated an operational system can be established more quickly. The Foundation's activities in this area would include funding of original research in this field, mining of previous research data for potential seismic correlations, and development of parallel space-based and ground-based systems to search for further correlations. On the policy side, numerous questions need to be addressed. How are warnings issued to the public? And at what stage of development of the early warning system should public forecasts be made? For the pilot period it is recommended that the Foundation issue any earthquake watches and warnings directly to the disaster response agencies in the focus countries, but that the agencies themselves have sole responsibility for any actions taken (e.g. evacuation of the local population) as a result.

The simulation and response prototype would be focused on better response effort coordination, education and outreach, expanded use of space technologies in disaster response, and computer simulations – potentially one day using early warning information as input – that predict where earthquake damage will most likely occur in a given region. A detailed discussion of the simulation and response prototype is outside the scope of this paper, but is available in the TREMOR report. [1] A separate paper focused on this aspect will be presented at the 2008 International Astronautics Conference (IAC) in Glasgow, UK.

TREMOR Space Segment

Three alternate satellite concepts were proposed as part of the early warning prototype and/or as part of a longer-term operational system, to be funded in whole or in part by the TREMOR Foundation. These concepts are described in the TREMOR report [1] and are summarized here.

2ESat Concept

The simplest concept involves two microsatellites in an 83° inclination drifting orbit, referred to as the 2ESat ("two earthquake satellites") concept. One satellite, referred to as 2ESat-U ("upper") would orbit at an altitude of 1000 km and perform ionospheric top-sounding. The second satellite, 2ESat-L ("lower"), would orbit at an altitude of 500 km and probe the lower structure of the ionosphere. Other suggested payloads for these satellites include ULF/ELF/VLF wave analyzers, plasma analyzers, mass spectrometers, and particle drift meters.

4ESat Concept

The second concept, 4ESat, incorporates four satellites in high-LEO (e.g. 800-1000 km), high-inclination (80° or above) orbits, providing ionospheric measurements with shorter revisit times than the 2ESat concept.

[3] This selection turned out to be sadly prophetic. Large earthquakes struck all three countries immediately before and during the 2007 ISU Summer Session Program: Yunnan Province, China (June 4; 3 fatalities), Niigata, Japan (July 16; 9 fatalities), and Ica, Peru (August 15; 514 fatalities). The latter occurred on the same day that the TREMOR final report was being prepared.

TSATS Concept

The third concept, TSATS (Tremor Satellites) is a larger-scale and longer-term concept involving four satellites in Tundra-type orbits as part of a future operational system. These orbits are elliptical, are critically inclined at 63.4° to avoid apsidal rotation, and have a 24-hour period designed to match Earth rotation.[4] The satellite ground track is repeating, with apogee and perigee always occurring over the same point on the Earth's surface. Near apogee the ground imaging resolution is poorest due to the increased distance from the ground, but a vast area of the Earth is visible to the spacecraft for prolonged periods due to the reduced orbit velocity and more distant vantage point.

One orbit option for the TSATS constellation is shown in Figure 4, with the ground tracks for the four satellites. Two satellites are assigned to the western and eastern hemispheres, providing coverage to the three focus countries, as well as to other important seismic regions. In each case, one satellite has its apogee in the northern hemisphere while the other has its apogee in the southern hemisphere. The satellites are phased such that for the vast majority of time there are two satellites above China/Japan – one at apogee, one at perigee – and likewise for Peru. This would make it easier to correlate potential precursor sources at different altitudes, as they would be sampled nearly simultaneously. The satellite designations here indicate the focus region (PE = Peru, CJ = China/Japan) and whether the satellite is at apogee (A) or perigee (P) over that region. The original designations from the TREMOR Report (S1, S2, S3, and S4) are indicated in parentheses. Because the orbits cross the equator, the satellites also pass over parts of North America and Australasia, thus offering coverage of other seismic regions in the "Ring of Fire". The fact that the four satellites occupy only two different orbit planes opens the possibility of a shared launch for each satellite pair. The downside is that to maintain a tight ground track over the focus regions requires a relatively high perigee altitude. In the case presented here, a perigee of 20,000 km has been assumed, which yields an apogee of 51,572 km.

An alternative concept is shown in Figure 5, in which only two satellites are used, with the apogee and perigee placed on the equator. Each satellite performs a "figure-8" ground track with a long dwell time over both focus regions. The perigee was assumed to be 1000 km, which yields an apogee of 70,572 km. Each focus region is accessible to the satellite for 80% or more of the time, with the disadvantage that perigee/apogee passage does not occur directly over the focus regions.

The apogee altitude would be far too high for SEME detection using ionospheric sounding or for SAR imaging (without a prohibitively large antenna), but low-resolution ground imaging related to earthquake monitoring (e.g. thermal IR) could still be performed. A small communications payload could also be included for supporting response efforts. At lower altitudes for the 1000-km perigee case, ionospheric EM science is a possibility. Ideally a SAR payload could be included to support tectonic stress monitoring, but would likely only be useable for short periods near perigee. It also remains to be seen how effectively SAR can be used in an elliptical orbit as opposed to a circular one.

Other ground-synchronized orbits could be employed to achieve repetitive coverage of the focus countries and other seismically-active regions. Elliptical 12-hour "Molniya" orbits or 8-hour "Cobra" orbits would be less expensive to launch and could be spaced to provide some coverage of the Mediterranean, Middle-Eastern, and South Asian seismic regions as well. Unlike the Tundra orbit, these orbits place the satellites in the Van Allen radiation belts for prolonged periods, which will reduce the operational life of the satellites and/or increase design costs related

[4] This type of orbit is presently used by the Sirius Radio satellite constellation.

to radiation hardening. A trade-off study can be performed to determine the most cost effective approach.

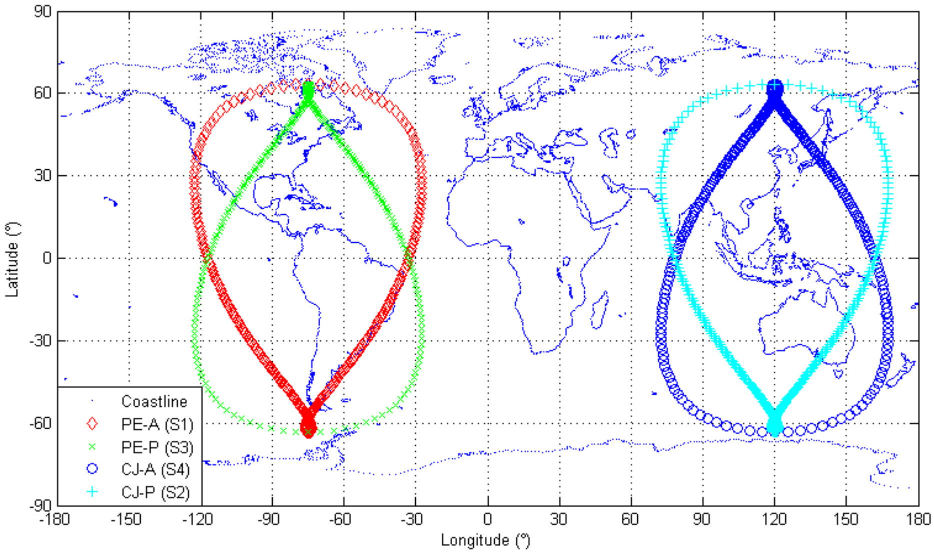

Figure 4: TSATS Constellation Ground Track

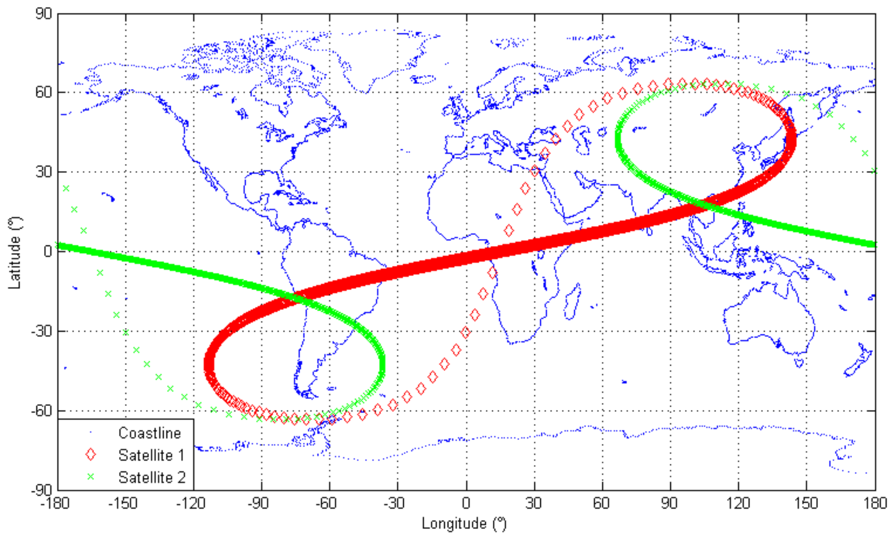

Figure 5: Modified TSATS Constellation Ground Track

Cost Model

The TREMOR report presented a cost model and financial plan for implementing the early warning and simulation/response prototype systems. The total costs to the Foundation over the 10-year pilot period were estimated to be USD 96 million, of which USD 42 million was apportioned for developing the 2ESat satellite system as part of the early warning prototype (USD 35 million plus 20% margin). The remaining costs cover the rest of the early warning prototype effort (e.g. data mining and storage, ground-based precursor research) plus the simulation and response prototype and overhead costs. [1]

The cost model presented in Annex B of the TREMOR report was a preliminary one, making some simple assumptions. The cost for the 2ESat concept was based on an average cost per unit mass from five earlier small satellite missions, obtained from the 3rd edition of Space Mission Analysis and Design (SMAD3). [25] For this current paper, a second iteration of the cost model was performed based on the parametric cost formulas in the Small Satellite Cost Model (SSCM), as supplied by the same reference. Launch costs are a large variable, but were assumed for this updated model to be USD 25,000 per kilogram. The revised estimate is shown in Figure 6 to be USD 31.2 million for both satellites (excluding margin), which is largely in agreement with the TREMOR report estimate. The 4ESat concept, which was not estimated in the original TREMOR report, is estimated using the SSCM to be USD 53.5 million for all four satellites.

The cost for the TSATS concept is more difficult to estimate, as the payload concept is not yet fully defined. It is certainly not expected to be a small satellite, however, and based on costs for other large spacecraft in high-altitude orbits (e.g. communications satellites) as reported in SMAD3, the per-satellite cost is estimated to be on the order of USD 100-200 million, or USD 400-800 million for the original four-satellite constellation. Inclusion of a SAR payload, if proved feasible, would increase this cost even further.

Component	Parameter	Unit	Value	Formula	RDT&E + TFU		Recurring (%)	2ESat	4ESat
					FY00$M	FY08$M		FY08$M	FY08$M
Bus	Bus mass	kg	80	0.781 + 0.0261 * X ^ 1.261	7.3	8.6	40%	12.0	18.9
Payload	Bus cost	FY00$K	7	0.400 * X	2.9	3.4	40%	4.8	7.6
IAT	Bus cost	FY00$K	7	0.139 * X	1.0	1.2	100%	2.4	4.8
Program	Bus cost	FY00$K	7	0.229 * X	1.7	2.0	50%	3.0	4.9
GSE	Bus cost	FY00$K	7	0.066 * X	0.5	0.6	0%	0.6	0.6
Launch	Spacecraft mass	kg	125	0.025 * X	3.1	3.7	100%	7.3	14.7
LOOS	Bus cost	FY00$K	7	0.061 * X	0.4	0.5	100%	1.0	2.1
Total						**20.0**		**31.2**	**53.5**

Figure 6: Cost Estimate for 2ESat and 4ESat Based on Small Satellite Cost Model

The Way Forward

Earthquakes remain among the deadliest of natural disasters in part because of the lack of any reliable system to provide early warning. In this paper, several possible earthquake precursors were examined. GPS and InSAR are both demonstrated and validated approaches for monitoring tectonic motion, the latter having the advantage of not requiring installation of ground receivers in tectonic regions. SAR is a relatively expensive technology, however, and to apply it on a global scale for continuous monitoring of seismically active regions will likely require a significant capital investment, unless enabling technologies arise that substantially reduce the cost of SAR payloads. The subject of electromagnetic and ionospheric precursors was also presented. EM activity has been observed prior to, during, and immediately after seismic events – both from the ground and from space – but turning this into a practical early warning system is another matter. The ionosphere is a highly dynamic environment, and in many ways still inadequately understood. Results from the first SEME satellite missions to date have been inconclusive, but have shown some interesting correlations that warrant further study. The payloads used in SEME research are also relatively simple and inexpensive, so these missions are typically much more affordable than SAR-based ones.

It must be emphasized that the science of earthquake precursors is still very much in its infancy. To be useful for an early warning system, an earthquake precursor must be observed and identified sufficiently in advance of the event (i.e. days or weeks, rather than hours or minutes), must indicate the geographic location of the event, and must be distinguishable from signals generated by non-seismic sources. To date, this has not been achieved using any approach. A practical early warning system, if realizable, would take many years to develop and would very likely depend on data from multiple precursor sources to ensure as accurate an assessment as possible.

This paper has also presented the concept of the TREMOR Foundation – an NGO dedicated to improving knowledge and capabilities in all parts of the earthquake disaster management cycle. As such its existence is not dependent on the feasibility of an early warning system, but it would obviously greatly benefit from one. Addressing the mitigation aspect of earthquakes includes advancing the state of earthquake early warning research, with an eye to ultimately implementing an operational early warning system should this prove feasible. During the pilot period, though, the Foundation will be largely dependent on government sources for funding. Where should the Foundation direct its limited financial resources to best support research and development in this area?

Before funding further spacecraft for SEME research, significant effort should be made to analyze data already collected, whether from the ground or in space, to identify any correlations not yet uncovered. Special data mining methods have already been developed to extract the important data from the noise (e.g. the neural network used by the DEMETER team) but the Foundation can still play an important role in funding the continuation of this work. If more correlations can be found in existing databases, this would strengthen the case for future SEME missions and make it easier to elicit funding for them.

For the foreseeable future, or at least while results are less than conclusive, SEME studies are likely to be limited to microsatellite and nanosatellite classes of missions. The TREMOR report recommended fully funding a two-microsatellite constellation. Given that there appears to be interest from multiple parties in doing further research on SEME from orbit (e.g. the ESPERIA, ELMOS, and CSES proposals), a different approach might be for the Foundation to coordinate with these existing groups and discuss a merger of their concepts and the TREMOR concepts. As an international NGO, the Foundation would be in a unique position to bridge the gaps between the interested parties in the different organizations and countries. Even if the Foundation cannot afford to fund satellite programs on its own, it can fund concept studies and can pool its funding with other interested organizations. In cases where a spacecraft concept is facing a competitive bid for funding, even a modest contribution by the Foundation could tip the balance in that concept’s favour by reducing the costs to the funding agency.

For SAR-based missions or multi-payload concepts like TSATS, the greater expense makes it impractical for the Foundation to fund satellite development on its own. Instead, the Foundation is best poised in these cases to serve as a public advocate for SAR/multi-payload satellite development, and to advertise itself as a key potential customer for their data products. The Foundation can also advocate for better co-ordination of satellite resources, such as recommending that different agencies select orbits that will provide better overall repeat times over seismically active areas. In particular, if the Foundation can demonstrate a financial incentive for improving such coverage – e.g. through the TREMOR subsidiary supplying data products to the insurance industry – this will strengthen its advocacy position further.

Many of the ideas put forward in the TREMOR report and in this paper have been discussed previously by other interested groups in many other contexts. Earthquake precursor science, both from space and from the ground, is being advocated simultaneously in several different countries. The concept of the TREMOR Foundation, as an international NGO, offers these groups a conduit and a way forward. Through co-ordination, advocacy, and funding, the Foundation would be in a unique position to bring these interested groups together and to focus their resources in the most effective manner. In forging such partnerships, the Foundation can make a difference – for those who research earthquake early warning systems, and for those who might one day benefit from them.

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